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Shape exploration of designs in a style: Toward generation of product designs

M. PRATS, C. EARL, S. GARNER, AND I. JOWERS
Department of Design and Innovation, Open University, Milton Keynes, UK
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Abstract

Generative specifications have been used to systematically codify established styles in several design fields including architecture and product design. We examine how designers explore new designs in the early stages of product development as they manipulate and interpret shape representations. A model of exploration is proposed with four types of shape descriptions (contour, decomposition, structure, and design) and the results of the exploration are presented. Generative rules are used to provide consistent stylistic changes first within a given decomposition and second through changing the structure. Style expresses both the analytical order of explanation and the synthetic complexity of exploration. The model of exploration is consistent with observations of design practice. The application of generative design methods demonstrates a logical pattern for early stage design exploration. The model provides the basis for tools to assist designers in exploring families of designs in a style and for following new interpretations that move the exploration from one family to another.

Keywords: Decomposition; Exploration; Product Design; Shape Rule; Structure

1. INTRODUCTION

Style is intriguing in its power of association between designs. At the same time the sources of this power are hard to identify. Generally, style is identified if similar features can be perceived in certain products created by one person, group of persons, across geographical areas, or through a period of time (Chan, 2000). However, as Chan claims, doing things in a similar way also defines a style. Therefore, style goes beyond similarities in perceived features and seems to speak of common intention. Thus, for example, a set of designs with no apparent similar features may be considered as the same style if a similar internal coherence, or composition, is perceived among them. In support of this idea, Smith (1981) argues that one style cannot be differentiated from others if there are no different parts and no different relationships among them. These relationships define the structure of shapes. Parts of designs, which we refer to here as elements, and structures of designs are central to this article, which provides a vehicle for creating and exploring new styles.

According to Arnheim (1974), structures determine the character and identity of shapes. He argues that structures are created in perception by the outlines of shapes, but outlines rarely coincide with structures. This suggests that structures and outlines are perceived at different levels of abstraction (Hoover et al., 1991). Arnheim argues that visual perception is dynamic, and therefore recognition of structure of shapes necessarily involves active participation of the viewer, for example, as proposed by Kepes (1944) for abstract paintings. If we accept that each shape possesses several different possible parts and structures, according to the way the shape is perceived, then style depends on an individual way of seeing that differs from other people's way of seeing (Gombrich, 1960). At the same time, in creative stages of design, designers seem to repeatedly change their ways of seeing (Schon, 1983). Chan (2000) argues that changes of style and emergence of new features can be used as an index to mark the creativity of an individual designer.

This paper seeks to gain an understanding of how designers develop and explore new styles in the early stages of

Reprint requests to: M. Prats, Department of Design and Innovation, Open University, Milton Keynes MK7 6AA, UK. E-mail: m.prats@open.ac.uk

product design. In particular, we concentrate on exploring styles that are defined through a designer's individual perceptions of elements or parts of the design and their spatial relations. As such, this approach to style is amenable to a generative specification where underlying rules, which express elements and structures, generate classes of shapes. This generative model for exploring new styles through formalization of perceptual elements and structures of designs suggests new directions for the development of computational design tools. Changes of perception offer points of departure for creation and exploration of new styles.

2. DESIGN EXPLORATION AND FORMAL APPROACHES TO STYLE

During design there are three possibilities: a new style is created, the same style is maintained, or a combination of both (Chan, 1992). Our investigation focuses on the first possibility where design alternatives are created and new styles are explored in the concept stages.

Applications of generative systems in design have demonstrated that aspects of style can be formalized (Stiny & Gips, 1978). Styles in this generative sense come from specific grammars and schemes of rules that create a consistent and unified corpus of objects. Simon (1975) provides a general view of such an approach, and several authors in the shape grammar literature (e.g., Stiny & Mitchell, 1978; Koning & Eizenberg, 1981; Duarte, 2005) provide cogent examples of generative schemes that satisfactorily explain the style of a corpus of architectural designs. Duarte has extended this approach to consider architectural styles whose instances are currently being designed and built, which are styles under development. Chen and Owen (1998) present a system capable of generating forms that exhibit defined stylistic properties. Other recent work has extended the generative specification of style to products. This includes specifying grammars for styles in engineering product designs based on curves by McCormack et al. (2004) who develop an extensive infrastructure for implementing parametric grammars (McCormack & Cagan, 2002).

Although many rule-based implementations have attempted to delineate generative specifications for designs in a style, the free flowing exploratory capabilities of shape rules have rarely been developed. In most approaches a defined style and type of product are maintained through the generative process. This narrow use of predefined style can be extended to include more temporary and tentative speculations on possible styles. These are created when designers look at an existing corpus in a predefined style, reinterpreting structure, regenerating details, developing the style, and seeking inspiration from its consistency and variety. Style in this wider sense is essentially dynamic and this paper examines the ways that designers iterate through interpretation, generation, and reinterpretation (Schon, 1983) to explore a style. Style becomes, in this view, a synthetic or constructive mechanism rather than an analytical or explanatory tool. However, generative explanations of existing styles are essential starting points for developing new styles and as sources of inspirations for new designs.

How does established style inform and inspire new designs? How is style developed through the processes of exploration and experimentation? These are the types of questions that need to be addressed if style is to be not only an inventive *post hoc* classification of intention and meaning but also a driver and inspiration for exploring possibilities. The model of exploration of style proposed here, although founded on the principles of generative design and on the application of shape grammars for generating spatial form, is not necessarily about discovering elegant or parsimonious descriptions of designs but is instead about the ways these descriptions are used for inspiration and expression. Such elegant descriptions can lack robustness, becoming cumbersome as intention and constraints change. It is tempting to look back over apparently consistent oeuvres in identifiable styles or to predict future characteristics of classes of generated designs in a well-defined "grammatical" style in order to find those designs that might meet intentions. However, neither scheme catches the essence of generative design, which lies in active synthesis of interpretation, generation, and reinterpretation. This exploration through synthesis looks ahead to new designs where style, as an encapsulation of current descriptions and knowledge, is a starting point for new departures.

The synthesis model described here concentrates on product design especially at preconcept and early concept stages. These stages demonstrate both a rich range of interpretations, through different ways of looking at shapes and their associated inspirations, as well as radical changes in shape and form through shape rule application. In early stages of design shape exploration may not be closely constrained by the semantics and function of the product being designed. Indeed, new generated shapes and their reinterpretations may assist designers' creativity as they search for new forms, semantics, and functions.

3. CREATIVITY, PERCEPTION, AND DESIGN DECOMPOSITION

Creativity includes the generation of ideas as a means of problem finding and problem solving. Suwa (2003) proposes that the coordination of perceptual reorganization and conceptual generation is central to creating novel interpretations and requires particular cognitive abilities. A crucial part of creative activities is discovering new interpretations. A designer may construct a sketch with one arrangement in mind but, on inspection, may see another arrangement enabling a new unintended interpretation (Schon, 1983; Goldschmidt, 1994; Suwa & Tversky, 1997; Suwa et al., 2000). These and other studies (for a review see Purcell & Gero, 1998) describe how designers use sketches in a range of cognitive processes and the kinds of design ideas that designers generate from sketches. Among many other findings, these studies indicate that new design ideas are frequently a consequence of reorganizing and then reinterpreting parts or elements in design representations such as sketches.

This exploration of the shapes of new designs is achieved through shape rules acting on (re)interpretations of shapes in sketches. A potential drawback to relying on rules is the view that new designs produced by shape rules in a grammar are not innovative but are implicit in the grammar (Kirsch & Kirsch, 1986). However, a countervailing view is presented by Stiny (2006), who argues that a strictly generative account of style neglects the new rules and interpretations created and applied as a style develops. The strictly generative account concentrates on a fixed set of rules explaining the final items in a stylistic corpus. The more flexible view of generative design is consistent with the approach to style adopted here, where the rules are defined (and discarded) progressively during the exploration process and not prior to the design task.

A design representation such as a sketch can be perceived in many different ways. Each such interpretation leads to a decomposition of the shape into parts with relations among parts (Stiny, 2006), which yields a starting point for exploring variations through the generative description. Wide ranging exploration at early design stages seems to depend on being able to jump between interpretations, to develop details within each, and to use these new details to prompt and inspire further interpretation and exploration.

In the method presented here, shapes are decomposed into elements according to how they are visually perceived. Particular decompositions can be used to recognize shapes and analyze their properties. In addition, decomposition of shapes into elements has been widely used by design researchers who seek to understand how shapes are generated in order to develop computational tools that are intuitively usable and understandable by designers. Projects such as FIORES I and II (Giannini & Monti, 2002; Cappadona et al., 2003) in the EU Information Technologies portfolio are collaborations between industrial product designers, computer scientists, and engineers. The methods used in these projects decompose shapes in order to explicitly communicate product esthetics and aid the development of interactive design tools.

Decomposition of shapes has been applied in several forms in shape grammar implementation, ranging from distinguishing shape features, for which separate generation rules are formulated, to hierarchies of subshape types that are subject to different freedoms and constraints in the assignment of parameters (McCormack & Cagan, 2002).

Although perception is much more complex than simply decomposing a shape, decomposition of shapes is an important part of perception. Given the elements in a visual decomposition, a modification applied to one or more of these shape elements results in a new design that is consistent with the designer's original perception. Consider, for example, the sequences of sketches illustrated in Figure 1, which we produced in a study of sketch exploration by industrial designers.

The sketches in Figure 1a are presented in the order they were produced; that is, the sketch on the left is produced first and that on the right second, although there are intermediate sketches. The first sketch shows the designer constructed the spout and body of the kettle by the same stroke, and in the second sketch the spout was produced independently from the body. Figure 1b illustrates a schematic representation of this modification. This suggests that the designer changed his initial perception of the concept design to identify a separate pouring spout in a particular relation to the body of the kettle. Figure 1c shows that the new

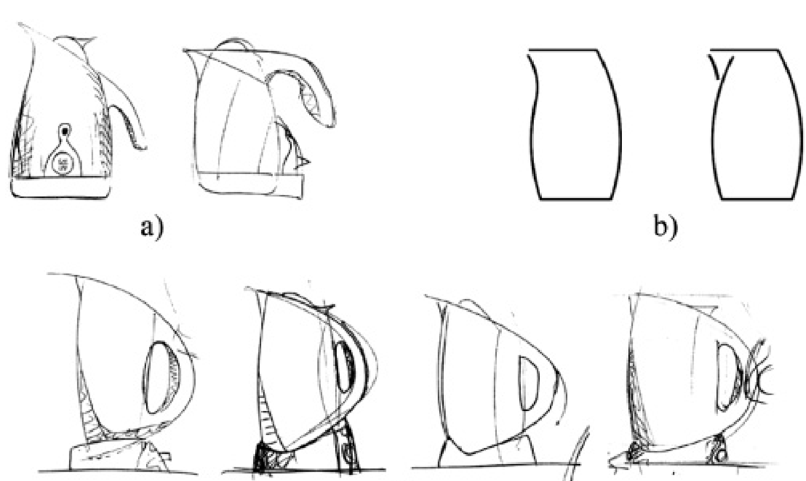

Fig. 1. (a) A sequence of sketches, (b) a schematic representation of the modification identifying a pouring spout, and (c) a sequence of sketches produced after reinterpretation.

interpretation with a separate spout was retained, at least for generating several subsequent designs alternatives. In this sense these alternatives were consistent with the designer's new interpretation of the shape with a separate pouring spout, corresponding to the new decomposition.

A new interpretation of a shape corresponding to a new decomposition can lead to a new design space. Moving from one design space to another changes the style and can promote exploration in quite new, creative directions. Consider the movement across design spaces in Figure 2 that starts from an initial concept design lying in a design space A. This initial concept is immediately reinterpreted (i.e., new elements and new relations or structures are perceived) as belonging to another design space, exploration proceeds in this space (i.e., the new elements are modified but the structures among the elements are maintained) until another reinterpretation shifts to another space C, and a sequence of modifications leads to the final concept design.

The generative model presented here has the potential to help enhance designers' creativity through aiding their explorations by interpretation and modification of shapes. It allows designers to formalize their own perception for each particular shape at any time during a design. This formalization is made through the addition of supporting shapes to the design. These are similar to abstract ordering devices such as grids and composition lines often used by designers that are not part of the physical concept design.

Supporting shapes are considered to be organized in separated layers of description in a similar way to CAD systems. In a sense these descriptions can also be considered at different levels of abstraction with elements and structure representing higher configurational levels than the physical shape of the outline. The additional layers of description promote new perceptions unintended by the designer, enriching creativity, through exploration of their consequences. An important feature of this process is that the designer has the possibility of exploring new shapes from different views and different levels of abstraction. For example, this accords with practice in early stages of the process when designers constantly move between abstract representations and attention to particular local details. Thus, especially for the early creative stages of product design, it is beneficial to be able to manipulate shapes or shape elements at different levels of abstraction.

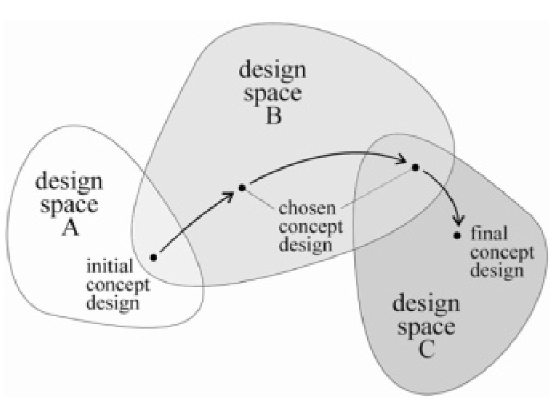

Fig. 2. Moving between design spaces by reinterpretation.

Following the discussion above on elements and relations in decompositions, two types of exploration can be immediately identified. These often work together during a design process, but they are clearly distinguished here. The first type involves exploration through modification of the elements perceived in an interpretation. The second type involves the exploration of relations among elements through modification of structure and relations between elements. In order to deal with these two types of exploration, four different descriptions are presented in separated layers, although one or more different layers can be used at a time. Section 4 establishes some details of the different descriptions and discusses how layers may assist design exploration. Section 5 presents a model for decomposing shapes into elements and examines how this may assist designers in exploring concept designs through modification of elements. Section 6 introduces the notion of structures and their application for exploring designs at higher levels of abstraction. Finally, Section 7 concludes that formal perceptual descriptions are crucial in order to make the computational synthesis process useful and understandable for the designer.

4. DESCRIPTIONS FOR EXPLORATION

One important aspect of the creative process is that shapes can be perceived and represented at different levels of abstraction. During the design process, designers may explore designs at a detailed level by focusing on specific elements of the shape while temporarily ignoring other elements. In addition, designers may explore designs at a more abstract level by focusing on the arrangement of the elements perceived in the shape. Designers often use regulating lines and other supportive shapes to assist the exploration of new arrangements of elements. In the creative stages designers constantly switch between different levels of abstraction. Hoover et al. (1991) argue that, while making a design refinement, the designer explicitly considers only those design object characteristics that are included within the current abstraction.

This is often a mental process and representations at the different levels of abstraction may not be rendered graphically. Two broad levels of abstraction are identified to help formulate the kinds of exploration that occur at the early stages of product design:

- level 1 deals with decomposition, so local details can be explored individually, element by element; and
- level 2 represents the arrangement of elements and thus the structure of the design.

In order to be able to deal with different levels of abstraction separately, layers containing distinct descriptions are employed. Layers separate and locate several pieces of visual information on the same image in an orderly way. For example, a CAD system may use different layers to place the shape, axis, dimensions, notes, and so on. Different layers can be associated so that a modification applied to one layer may affect associated layers. For the purposes of our study, four associated layers are used: contour, decomposition, structure, and design. The intention is that layers can be turned off in the model, making the information invisible, and users can explore any abstract level individually. For instance, one might want to concentrate just on exploring new structures, so the other layers can be turned off. Once some candidate structures are found, the design layer can be turned on again in order to see the new designs produced by the new structures.

The *contour layer* is where the outline, often in the form of a sketch composed of geometric elements representing the initial concept design (initial idea for a design), is placed. This layer is used for adding or subtracting elements as well as for introducing a whole new design concept. Two examples are chosen to illustrate the way the model works: abstract geometric designs based on interlocking curves and a functional design representing a jug kettle (Fig. 3). The explorations observed in a study of industrial designers are shown to closely mirror the types of exploration on these shapes. Indeed, the industrial designers in the study explored concept designs for jug kettles.

Figure 3 shows two examples of initial concept designs: a geometric shape composed of three interlocking circular arcs or three petals and the outline of a functional product design (a jug kettle) shape without crossing lines. Note that shapes with crossing lines tend to be easier to perceive in a variety of interpretations. At each crossing point there is more than one choice.

The *decomposition layer* contains the information of the shape decomposition. It formalizes all the elements identified in the shape and all the constraints applied to them. An element is a piece of the outline of the shape. A shape can be decomposed in infinite ways according to different perceptions. Several different decompositions may be explored at the same time. The decomposition layer is used when exploring variations in the detail shape of a particular element. Although these types of variation often generate similar designs, some variations can lead to a radical change of the whole shape. However, even more radical changes will be consistent with a designer's perception because relations as well as elements can be modified.

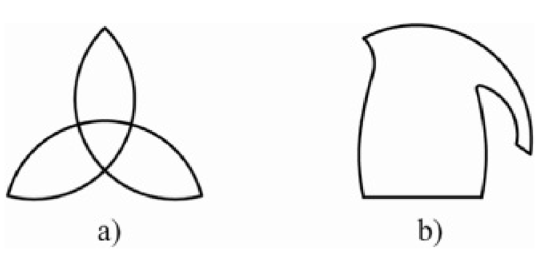

Fig. 3. Two representative shapes constructed from curved arcs.

The *structure layer* formalizes the interpretation of the grouping and arrangement of elements. The formal representation of the arrangement of elements is again by means of shapes on the structure layer. Rules applied to these shapes change the structure and will implicitly define new parts. In a sense the structure layer contains an abstract view of the whole shape composition. Structures are formed from groups of elements, and several different structures may be identified for a particular shape. The design layer contains the actual shape of the new design and is the point of departure for further exploration.

5. DECOMPOSITION INTO ELEMENTS

Decomposing shapes into elements assists analysis and exploration of shapes (Stiny, 1994; Krstic, 2005). However, the ways that shapes are visually decomposed is often unpredictable, although for certain shapes many people decompose them into similar forms. For example, the decomposition of the shape of a spoon will tend to be decomposed into separate elements (handle and scoop) according to their function. The number of different decompositions of an abstract nonfunctional shape may be higher, but common preferences are also observed. Biederman (1987) argues that human vision tends to perceive shapes as a set of primitives. Singh et al. (1999) argues that, if a silhouette can be decomposed in more than one way, human vision prefers decomposing it using the shortest cuts cross the silhouette. Gestalt theory also suggests common perceptual preferences among people. Consider, for example, the logo of the Audi car brand shown in Figure 4.

It is a shape that can be decomposed in several forms. Figure 4b and c show two examples, but most people would decompose it into four circles, perhaps because of the Gestalt principle of continuity that predicts the preference for continuous shapes such as the contour of the circle. Similarities in decomposing shapes suggest the possibility of decomposing shapes in well-defined ways. However, in the process presented here decomposition is not prescribed or defined beforehand because creative people perceive shapes differently; they *break rules* of perception in the design process. Rules are used here as a means for the designer to express intentions and generate new shapes that are consistent with perception and intentions, that is, to explore a style.

A shape decomposition identifies the limits of each perceived element. The designer might mark the limits of perceived elements with breaking points or *decomposition points*. The decomposition points are placed in strategic places on the contour at perceived points of discontinuity that generally coincide with the intersection of two or more lines (and/or curves), line (or curve) end points, or intersections produced by perceptual extensions of lines (or curves). Tapia (1999) and McCormack and Cagan (2002)

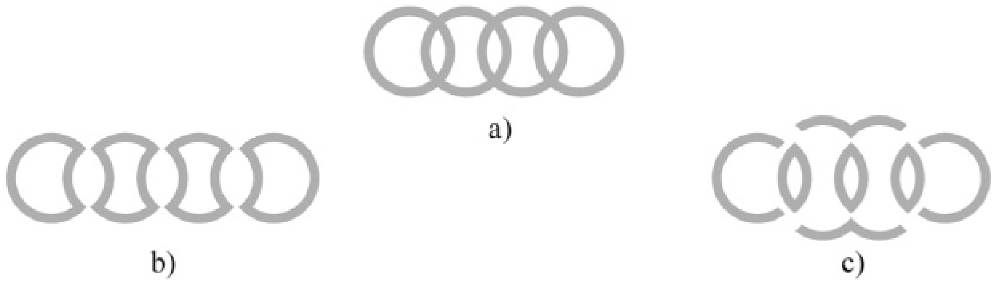

Fig. 4. (a) An Audi logo and (b,c) two different decompositions. Note that in order to illustrate the decompositions in (b) and (c) the perceived elements are separated from one another.

use this idea of points of discontinuity to assist shape matching in their computational implementations. However, sometimes during the design process the decomposition points may also be perceived to lie on smooth curves. Consider Figure 5a as an initial shape forming one of the petals in Figure 3a. Such a simple shape can be perceived differently, for example, as the contour of an eye (Fig. 5b), the contour of lips (Fig. 5c), or blender blades (Fig. 5d). Suppose that the shape is perceived as the contour of an eye. In exploring new variations it may be decomposed as upper and lower parts of the eye. Hence, the decomposition points illustrated with circles are placed on the two points of discontinuity of the shape (see *X* and *Z*, Fig. 5a). During the generation process, the points of discontinuity are kept fixed and the outlines that unify the two points are modified in order to explore new appearances of the eyes. This decomposition is perhaps the most obvious because it directly uses the two points of discontinuity. Using decomposition points, which do not lie at points of discontinuity, leads to significantly different shapes during modification, as illustrated by the lips or the blender blade in Figure 5c and d.

The decomposition points are normally placed on the contour line, although exceptions are not precluded and there is no formal limit to the number of decomposition points. The decomposition points identify possible elements in the contour. Each element can be represented by a *decomposition line* that joins the two extremities of each element. Decomposition lines are supportive shapes that assist the formulation of the shape rules, but they are not part of the final design. Many elements and corresponding decomposition lines can be constructed from one set of decomposition points. Figure 6b, c, and d show different forms of unifying the same decomposition points in Figure 6a. The shapes on the right side of the arrows show possible manipulations of the outlines defined by decomposition points and decomposition lines.

Once the decomposition points and decomposition lines are specified, a new shape appears made of straight lines. This shape or *diagram of elements* can be considered as an explicit picture or representation of the perceived elements, which indicates where to explore shape modification of elements and, further, new arrangements of the elements.

Figure 7 shows different diagrams of elements. The star-like diagram (Fig. 7a) and the triangle diagram (Fig. 7b) suggest that the shape is perceived as a balanced composition. Figure 7c decomposes the jug kettle shape into four elements, which do not follow any recognizable pattern, and Figure 7d decomposes the same shape into six elements following a recognizable pattern. It is possible to give a name to each element: base, front main body, spout, lid,

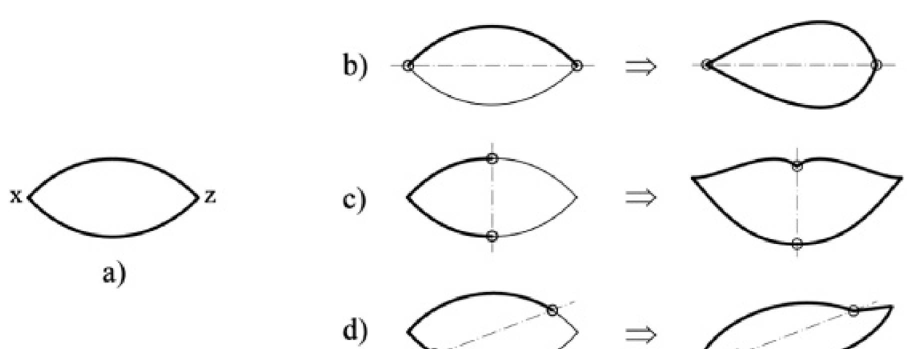

Fig. 5. Three interpretations of (a) a petal shape using different decompositions: (b) at points of discontinuity, (c) bilaterally symmetric points on the curves, and (d) rotationally symmetric points.

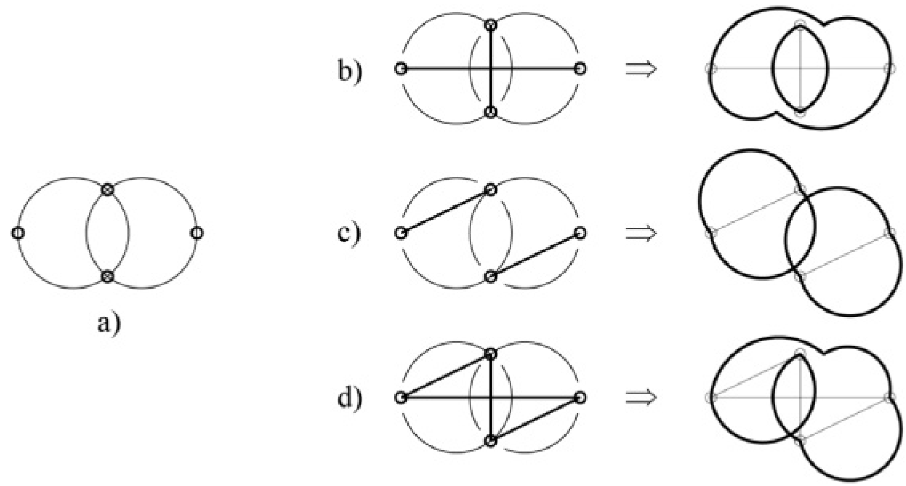

Fig. 6. Different pairings of decomposition points indicate different decompositions.

handle, and rear main body of the kettle. This last decomposition was based on functional judgments, whereas the previous ones in Figure 7a, b, and c were more concerned with esthetic judgments such as balance and symmetry.

Decomposition points and decomposition lines are placed to explicitly define the perceived decomposition of a shape. However, this is often not enough for shapes containing crossing lines. Figure 8a shows three different interpretations (as heavy arcs) of the same decomposition lines. Each interpretation is formalized with a shape rule, or *decomposition rule* (D1, D2 and D3), which adds the perceived outline (thick line) to the decomposition line. The application of decomposition rule D1 to the starlike diagram reconstructs the shape from elements making up the petals. Rules D2 and D3 are two more reinterpretations that, apart from also reconstructing the initial concept design, can produce unexpected and interesting designs in synthesis stages; they are unexpected from the standpoint of the original perception and decomposition. Single arrows are used to define the rules, and double arrows indicate application of the rules. Figure 8b shows new designs generated by the manipulation of the outlines with new decomposition rules (D1′, D2′, and D3′). Note that the new designs are placed in the design layer and that the contour layer that contains the initial design is not illustrated.

The interpretations are created from the decomposition lines by the application of decomposition rules. The simple example corresponding to the initial interpretation is shown in the top row in Figure 8 whereas more complex decomposition rules create the reinterpretations. Frequently, shapes in product design are more complex than these examples with several different elements being perceived in one shape. Elements are not always symmetrical or repeat across the shape. Corresponding decomposition rules might then add any element to any single decomposition line in such a way that a huge number of inappropriate combinations would emerge. Consider Figure 9, for example, where decomposition rules corresponding to the same diagram of elements presented in Figure 7c can generate widely differing designs. The associations between lines and curved elements expressed by the decomposition rules are all present in the initial interpretation. However, in these examples the decomposition lines are not distinguished from one another; thus, the rules used in different positions give rise to radically new shapes as the rules are applied.

The variety of generated shapes can be limited by using labeled points, although different types of labels can also be used. The position of the points relative to the lines specify not only in which decomposition line each outline has to be placed but also the right position for unsymmetrical out-

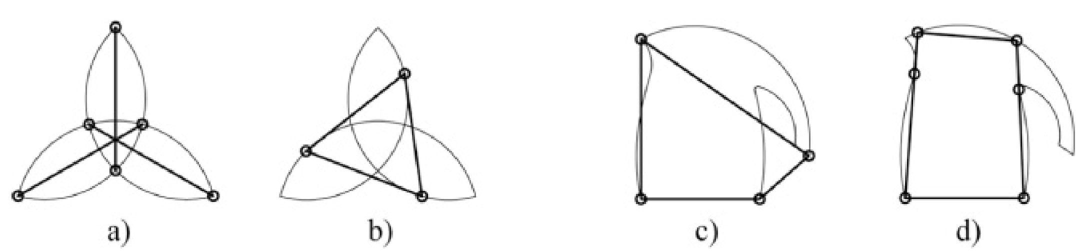

Fig. 7. Decomposition points and decomposition lines indicating elements.

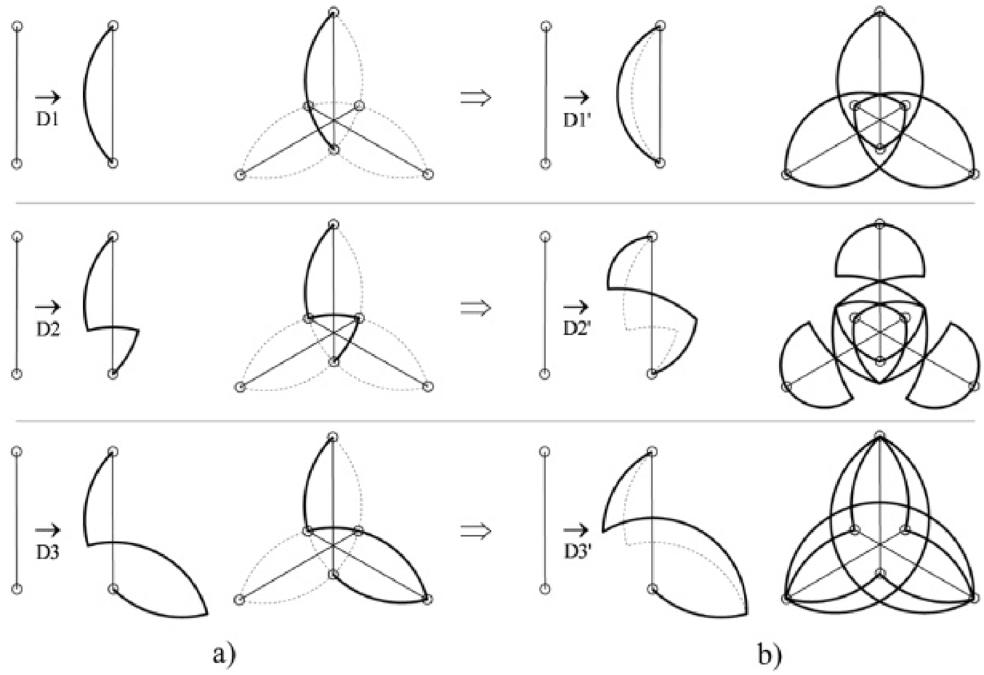

Fig. 8. (a) Decomposition rules reconstruct the initial concept design from decomposition lines and (b) variations in the decomposition rules generate new designs.

lines and the side of the decomposition line on which the outline is to be placed. Figure 10 shows that each outline corresponds to a different combination of decomposition line and point. Once labels are defined, the user gets one reconstruction, which is the initial shape redrawn and ready to be explored. During the exploratory stage, the user may want to totally or partially ignore the labels with the purpose of increasing the number of design alternatives.

In the decomposition layer new designs can be explored in two different ways:

- by manipulating the outline of elements according to predefined constraints and
- by manipulating the decomposition lines, leading to changes in the diagram of elements.

Any new designs generated in these ways will be composed of the same elements. Hence, the new designs will be consistent with a designer's interpretations and therefore will have a similar style, at least according to the designer's perception. Each gives more or less radical designs. For example, manipulating the outlines of elements in Figure 7a generates Figure 11a, whereas manipulating the decomposition lines generates Figure 11b. Both new designs illustrated in Figure 11a and b can still be decomposed into three petals, consistent with the perception of the initial concept design. Manipulating decomposition lines appears to lead to more radical designs. Figure 11c shows an example of exploring new jug kettles by manipulating the outline of the elements. The appearance of the object has been changed but strong similarities are still evident because the diagram of elements has not changed. Figure 11d provides a modification of decomposition lines leading to a more radical change in appearance.

6. ESTABLISHING STRUCTURES

Once interpretations of an initial shape are formalized by decompositions and associated decomposition rules, the

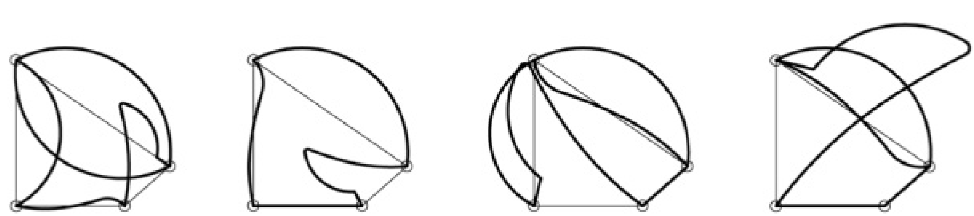

Fig. 9. Rules corresponding to the decomposition in Figure 7c give rise to new shapes when applied to the decomposition lines.

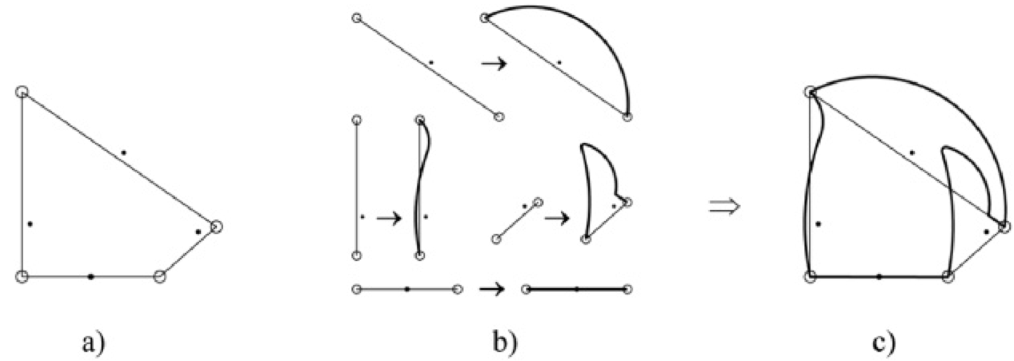

Fig. 10. (a) A diagram of elements and (b) a set of labeled decomposition rules. (c) The labels allow the initial concept design to be uniquely reconstructed by the decomposition rules.

designer can explore the new design space by manipulating the outline of elements and decomposition lines. Designers may group several elements and explore different spatial relations between groups in order to achieve a logical internal organization of the whole shape. This internal organization assists designers in designing complex compositions. It is an important aspect of style that gives coherence to a range of products. The method presented here groups one or more elements through a structure defined by the designer, which is placed in the structure layer. In a manner similar to the shape descriptions of decomposition, the structure is described by shapes of *structural lines*. Lines are a straightforward shape description of structure; but other structural shapes, such as circles and arcs, may be more effective representations as aids to exploration. Dashed thick lines are used to represent structural lines in order to differentiate them from decomposition lines. The key in Figure 12d shows the types of lines used to represent each layer. The structural lines shown in Figure 12b use decomposition points as end points whereas those in Figure 12c identify a particular bilateral symmetry. However, two questions arise. Does it make sense to define decomposition points that are then ignored in the structural decomposition? Why should decomposition into elements differ from structural decomposition?

Studies reveal that humans perceive the shape of objects in two different ways. For instance, Rudolf Arnheim (1974) argued that shape refers to two different qualities of visual objects. The first quality refers to the shape actually seen and the second quality is constructed cognitively. Similarly, Erle Loran (1943), in describing Cézanne's compositions, argued that one might consider that there is a surface structure and a deep structure within an artwork. Surface structure corresponds to many of the observable properties, like lines and colors, whereas deep structure refers to how the artwork is organized. Similar categories were presented by Birkhoff (1933) in establishing an esthetic measure and Stiny and Gips (1978) in developing general computational models for criticism and design.

Following this distinction, it is possible to distinguish the perception of the structure and elements of the same shape. Each one deals with different qualities at different levels of abstraction. Consider, for example, Figure 12b and c. On the left-hand side two similar shapes are decomposed into similar elements, but different structures are defined. That is, both shapes are perceived as a composition of three petals (see Fig. 12a) but with different relations between them. The structure and its marks shown in Figure 12b suggest that the whole shape is seen as a petal rotated three times. Such a structure could be the shape of a fan. In contrast, the structure and marks in Figure 12c form a span across the shape, suggesting that the shape is seen as one individual petal and two more mirrored petals. Such a structure might suggest the shape of an arrow or rocket. The shape rules (R1, R2, and R3) are referred to here as *relation rules*, and

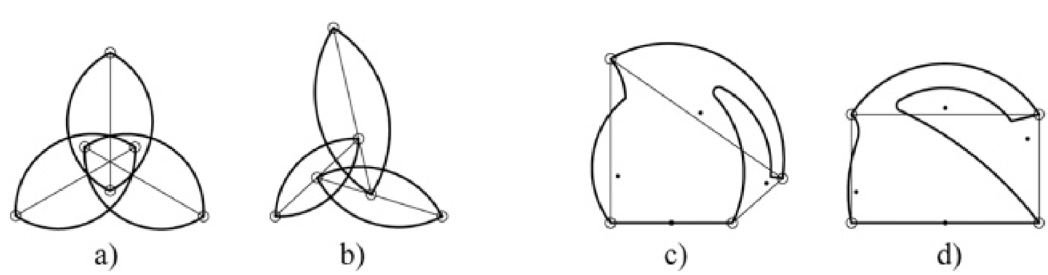

Fig. 11. Modifying the relations among decomposition lines.

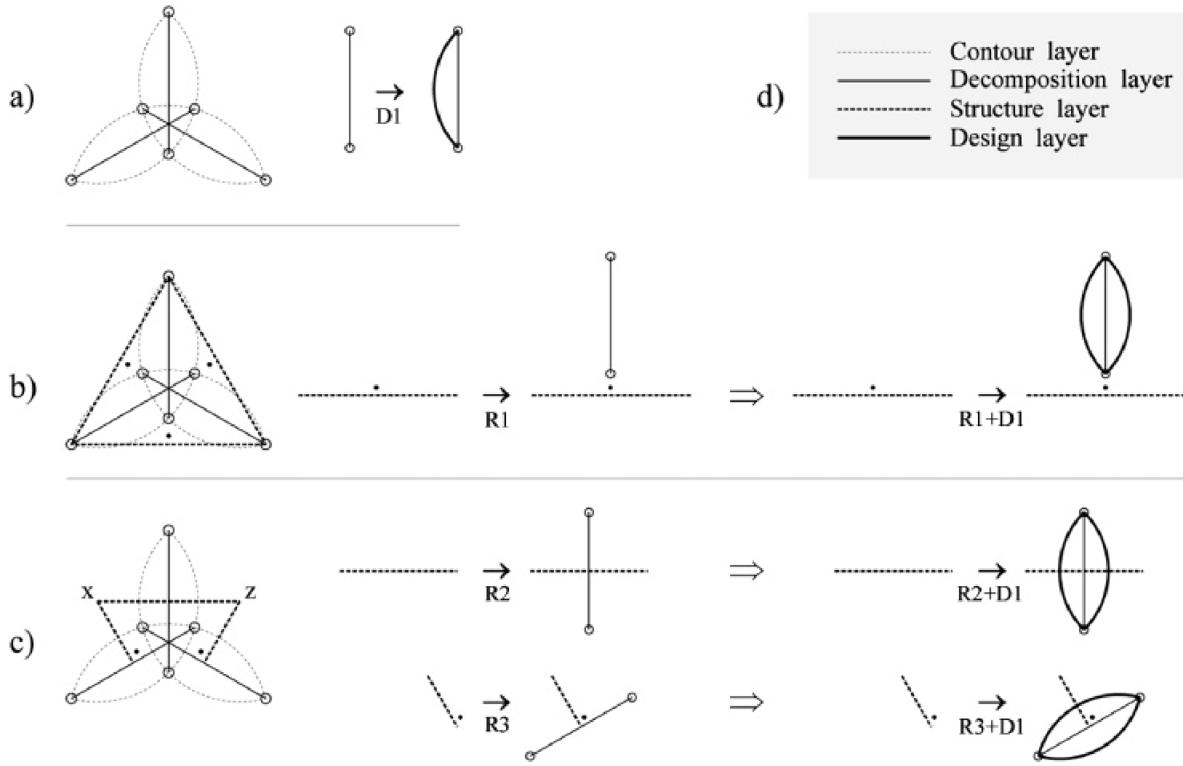

Fig. 12. (a) Structure layer shapes indicating (b) full symmetry of the three petal shape and (c) bilateral symmetry. The relation rules express relations between the structure lines, decomposition lines, and elements of the shape.

they express the relations between structural lines and decomposition lines of the shape. In order to visualize the relation between the elements and structure, the decomposition rule is applied inside the relation rule. These composite rules R1 + D1, R2 + D1, and R3 + D1 are shown on the right. These relation rules reconstruct the shapes from the structure and generatively describe the structure.

The main purpose of structure decomposition is to reveal and explore shapes through visual relationships between elements or group of elements. The structure is used to give visual coherence and beauty to designs. Unlike the decomposition into elements, the structure is not embedded or aligned with the outline of the shape. For example, the structural lines in Figure 12c share two common points (x and z) that are exactly the center points of the circular arcs that constitute the petals. These center points are not embedded in the outline but are outside the shape. This is a simple cognitive construction using geometrically significant points (referred to here as *strategic points*) such as the center of a circular arc, but any points can be chosen according to intention. Although strategic points may also include perceived points of discontinuity, their identification depends more upon subjective criteria than perceptual "laws." Hence, the definition of strategic points is more flexible than points of discontinuity.

In a similar way to decomposition into elements, the definition of the structure is subjective as well as dynamic: a designer defines a structure, explores, sees, describes a new structure, and so on. New designs can be explored in two different ways on the structure layer:

- by manipulating spatial relations between the structural line and decomposition lines and
- by manipulating spatial relations between different structural lines.

The illustrations in Figure 13c and e show exploration of the first type and Figure 13d and f show exploration of the second type for structures defined in Figure 12.

Figure 13c and e show two designs created by manipulating the relation between structural lines (the surrounding triangle of dashed lines in Fig. 13a or the "span" in Fig. 13b) and the decomposition lines (the three lines across the axes of the petals) through relation rules. In the relation rule R1′ + D1 the decomposition line has been rotated from its center. In the rule R2′ + D1 the decomposition line has been scaled, and in the rule R3′ + D1 the decomposition line has been rotated and scaled. In a similar way to Figure 12, the relation rules in Figure 13c and e are composites of rules (R1′, R2′, and R3′) that change relations between structure and decomposition lines and rules (D1, D2, and D3), which add the elements to the decomposition lines. Figure 13d and f show new designs created by manipulating the relations of structural lines through shape rules,

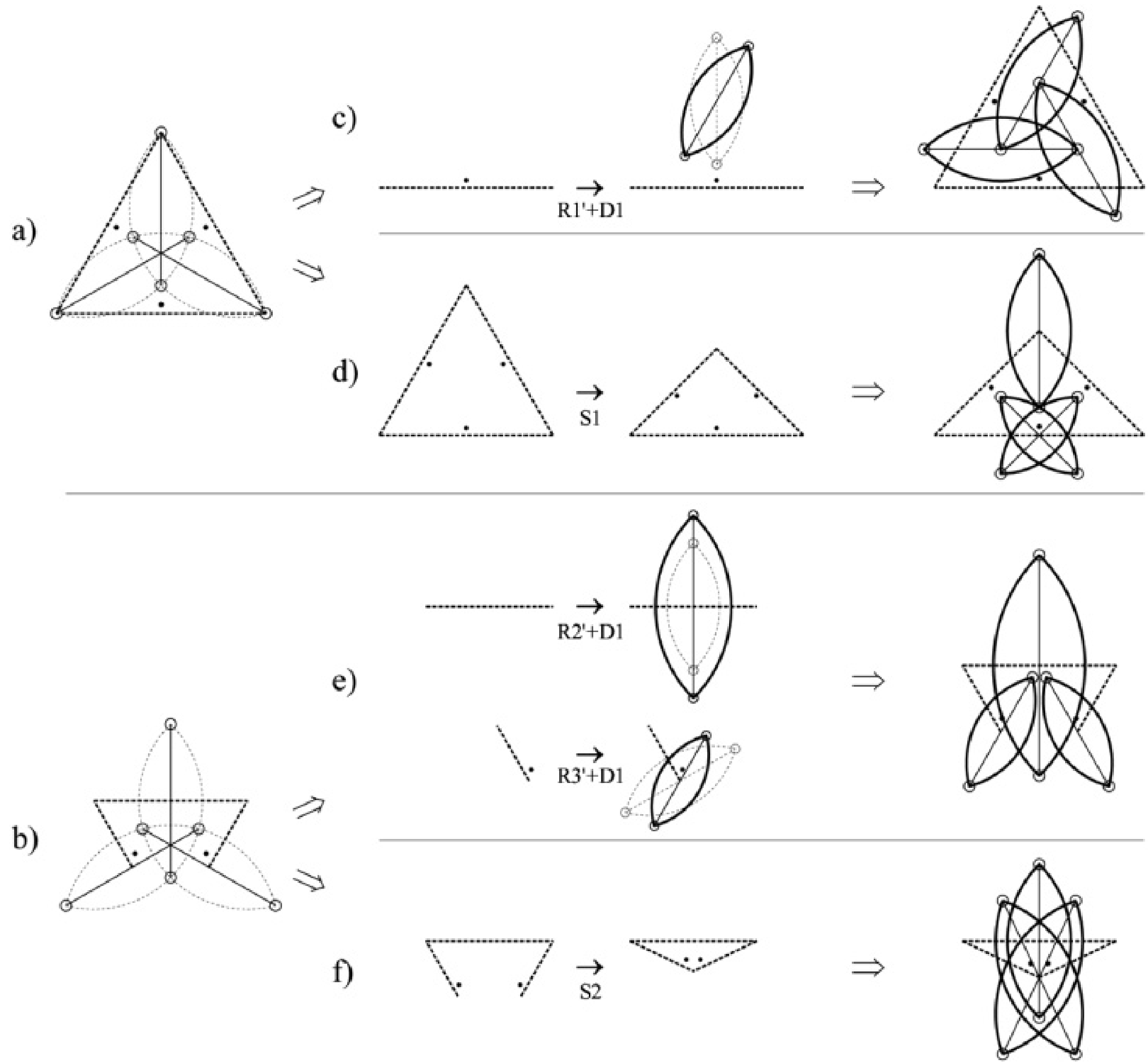

Fig. 13. (a, b) Structures defined in Figure 12; (c, e) modifying the relations between structure and decomposition lines through relation rules R1′, R2′, and R3′; and (d, f) modifying the relations between different structural lines through structure rules S1 and S2.

here referred as *structural rules* (S1 and S2). Composite rules S1 + D1 and S2 + D1 create the petal design. In this case the angles between structure lines are changed while incidence is maintained. Structural rule S1 scales the structure along the vertical axis whereas structural rule S2 rotates and scales two structural lines in order to obtain a closed structure.

As indicated above, the identification of structure is open to a wide variety of choices and interpretations. Figure 14a shows "strategic" points associated with a shape that could be used for defining the structure. The top and lower designs shown in Figure 14b use straight lines as a guide line for a group of elements, but the design in the center uses circular arcs. In these three examples a group of two elements makes a petal because of it was previously defined with rule D1. Once structure shapes are defined (three examples are given in Fig. 14b, which shows strategic points identified with circles), the structure can be manipulated in such a way that the resulting shapes follow perceptually interesting patterns. Figure 14c illustrates several examples.

Introducing structure makes the design space larger. When the designer decomposes a shape into elements, the design space, at least in terms of shape, is actually being narrowed down through selection from unlimited potential decompositions. At that level the spatial position of each element is not considered. However, as soon as the structure is defined, more variables (the spatial relations among elements) are brought into play and the design space is potentially expanded again. Exploring changes to the structure shape (e.g., the structural lines) can result in a radical change of the design shape. When the designer is satisfied with a certain structure, the design space can be narrowed down again by fixing the structure and concentrating on manipulating the outline of elements. New sketches can be generated by

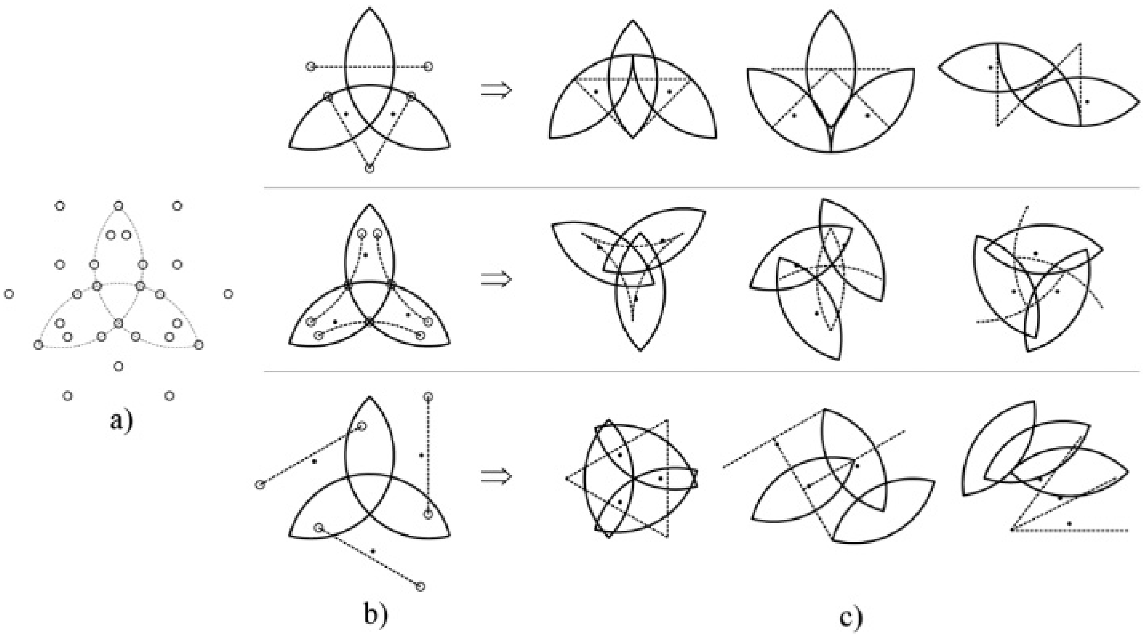

Fig. 14. (a) Strategic points, (b) a definition of structure by selecting strategic points, and (c) reconfiguring the structure lines with associated changes to the shape.

manipulating fine details of an initial design concept, but if designers do not see any potential they can change the structure. This is achieved by adding, subtracting, or changing the spatial relations between elements and is effected through rules on the structural shape.

7. GENERATIVE SHAPE EXPLORATION

This generative shape exploration model has essentially three steps: interpretation and decomposition, analysis and generation in the structure shape to broaden exploration, and reinterpretation and refinement. This can serve as a model of the design process of product designers in the early stages of design, which forms a basis for building computational aids for exploring product design spaces. The examples shown above with particular generative shape descriptions for decomposition and structure shapes illustrated how such a computational tool works. Current research includes developing such exploratory generative tools for product design. In particular, the application of formal shape rules and implementation of curved shape embedding are integral parts of the implementation of this model.

As shown in Figure 14, the structure shape can be manipulated by hand without constraints on possible changes. However, more systematic explorations of new structures can be achieved through well-defined rules in a computational implementation. Two simple examples are illustrated to summarize the explorations examined in this article. Figure 15 provides an example of exploring new structures of a shape perceptually composed of two groups of elements, R1 + D1 and R2 + D2. Each group of elements is represented by a structural line "strategically" positioned according to the intentions of the designer. Here, the rules define possible spatial relations between two structural lines. In this example, structural rule S1 adds one structural line to another line found at 90°, resulting in a T-shape. Structural rule S2 adds one structural line to another line found at 90°, resulting in an X-shape.

While exploring new structures, a new decomposition into elements can be included that corresponds to a new interpretation. Figure 15a shows the same initial shape interpreted in two different ways. The curve segment elements are different but grouped similarly in the structures. Structure rules S1 and S2 are applied with each of the decompositions R1 + D1 and R2 + D2.

Another example of this wide ranging exploration is shown in Figure 16 with the same initial shape and structure rules as in Figure 15 but with different decomposition points, lines, and rules (D3, D4, and D5) as well as different relations rules R3 and R4 between the decomposition lines and structure lines.

This paper introduced a method that enables designers to formalize individual perceptions of shapes in creative stages of design. It concentrates on the manipulation of outlines for product design. Here, the term formalization refers to a set of shape rules that explicitly reveal a particular perception of a shape. Stiny (1994) elaborated the mechanisms through which decomposition could be applied in shape generation, especially in identifying continuous and consistent interpretations created through rules. Each decomposition that describes the shape can correspond to a different perception.

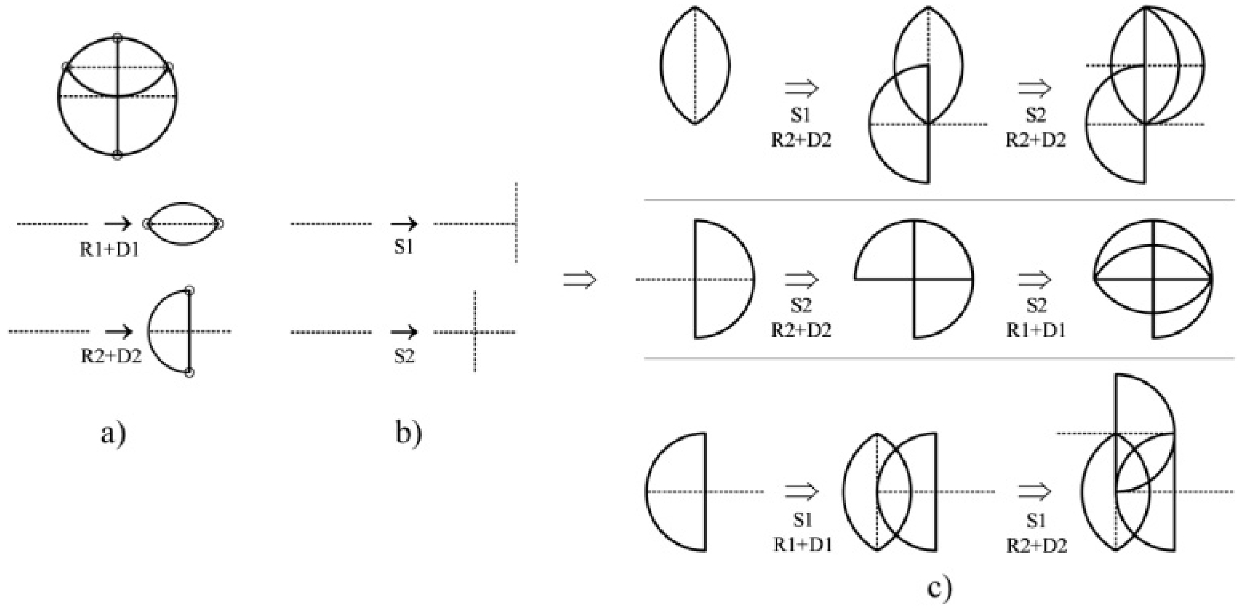

Fig. 15. (a) Initial concept design and relation rules, (b) two structural rules, and (c) shapes generated by rules that create new structure shapes.

The perception of a shape can vary from person to person. Often, the reinterpretation of shapes plays an important role in creative activities. Designers constantly change their interpretations during the exploration process in order to produce creative designs. The aim of this work has been to provide a model to be able to describe how designers identify their individual perception of a shape at any stage in design. Further, the model shows how the consequences of particular perceptions can be explored through generative shape mechanisms and suggests areas where computer support in generating creative designs would be applicable. By concentrating on the exploration of product designs, especially shape, through using shape rules, embedding this exploratory model of style in a computational tool is formally possible. Indeed, our current research shows that it is practically feasible. The application of generative shape

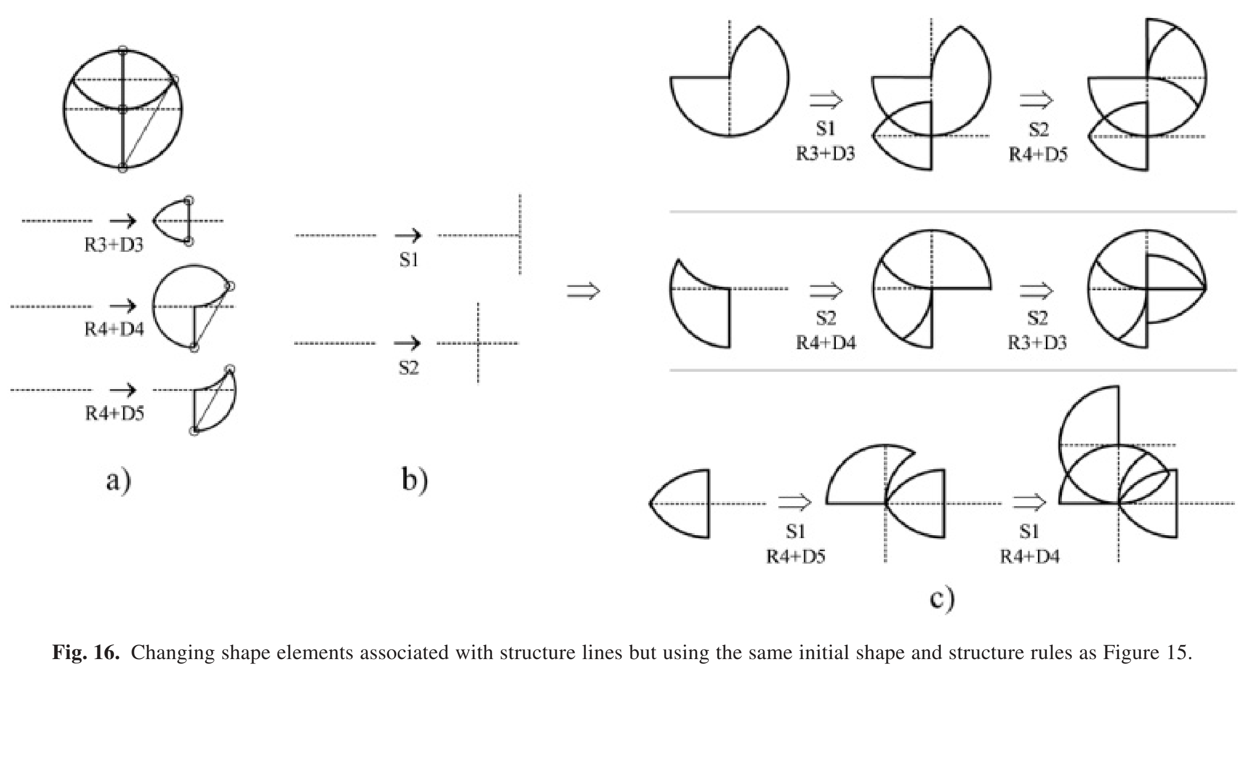

Fig. 16. Changing shape elements associated with structure lines but using the same initial shape and structure rules as Figure 15.

descriptions to explore designs that are consistent with designers' perceptions has provided insights into product design processes and indicated where computational tools might be useful. This consistency is crucial in order to make the process understandable for the designer and corresponds to maintaining designs within a style while simultaneously developing and exploring the style through new interpretations and new rules. In particular, tools that can assist the designer in exploring and developing style through interpretation, change, and reinterpretation go beyond the analytical generative account of style to one that is synthetic and exploratory (Stiny, 2006). The tentative suggestions in this paper go some way toward this goal. Our current research in the rules and methods for the exploration of the curved shapes in the four descriptions (contour, decomposition, structure, and design) uses a variety of generative shape descriptions for curves (Jowers et al., 2004; Prats et al., 2004).

This program of using generative shape descriptions to explore and develop new designs can be considered as an iteration of shape analysis and synthesis that is repeated on small and large scales through a product design process. The preparatory stages of interpretation, decomposition, change, and reinterpretation explore perception and inspiration. They set down the framework for shape generation of new designs as new insights and interpretations occur. The whole process is iterative. The design processes modeled in this article are essentially exploratory, not being governed by preconceived rules, but are free to create rules to follow inspiration, perception, and interpretation. More detailed explorations of outline and shape can be undertaken in a similar but geometrically more detailed way through shape rules applied to the elements in a product outline.

Recall that one driver for this research on design exploration was the examination of sequences of exploratory sketches (an excerpt is illustrated in Fig. 1) produced by industrial designers. These were created in response to a particular task to explore the outlines of jug kettle designs. The explorations undertaken by the industrial designers can be mirrored by the more formal explorations in decomposition and structure. Further stages in this exploration include progressive refinement of design families. Figure 17 shows examples of this refinement applied to the jug outline used as an illustration at various points in this work. The two frames show two sets of related designs or design families based on different types of shape elements in their outlines. Shape rules modify elements in the product outlines to create product families of related designs in a style. These families can be selectively refined. A specific design is selected from a family and variations are generated with fewer and fewer obvious differences.

The early stages of product design are characterized by extensive explorations of possibilities. Generative shape descriptions offer a route to formalizing some of the activities in this exploration. In particular, we propose a tentative model in which four shape descriptions of contour, decomposition, structure, and design are developed side by side. Some of the generative shape rules apply across two or more of these descriptions, so that changes across descriptions are related. Further, rules apply to change the spatial relations between shape elements across two or more descriptions. Styles used by designers are based on the interpretations and views expressed in these rules. It has been proposed that styles are not only static explanations of existing designs but are also the means to explore new possibilities. Styles expressed by contour, decomposition, and structure descriptions offer starting points for exploration through changing the spatial relations between the different descriptions. This exploration presents designs consistent with the individual descriptions and structure.

These consistent stylistic changes provide the basis for assisting designers to explore the consequences of their interpretations and structural views without being prescriptive. We provided examples of the different descriptions and their implementations in terms of rules. This research forms part of a larger program to understand the generative and exploratory activities in the early stages of product design. The proposals for assisting designers outlined here are continued through the systematic generation of design families.

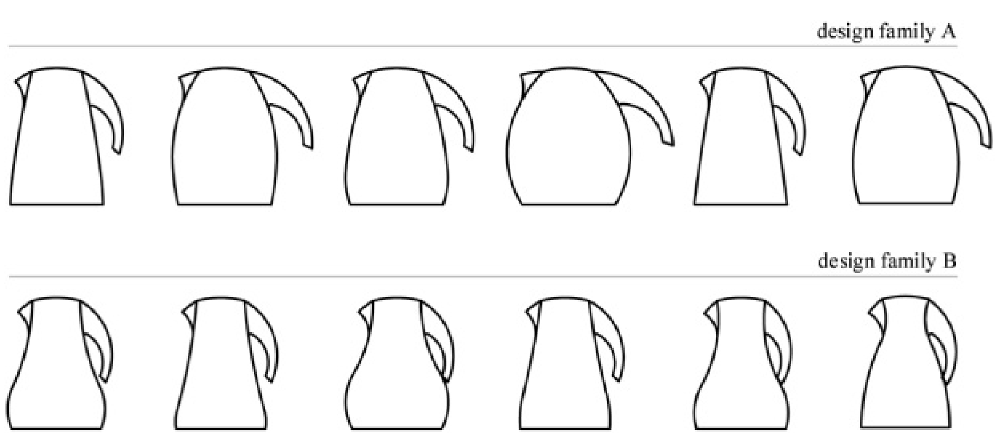

Fig. 17. Design families.

Generative shape descriptions mean that radically new interpretations can be developed at any point. On the one hand, generative shape descriptions analyze and explain; on the other hand, they synthesize and explore. The account of style in this article encompassed both explanation and exploration. Our continuing research is developing computational methods to assist product designers to represent interpretations, generate designs, and explore styles.

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Miquel Prats is currently completing his PhD in the Department of Design and Innovation at The Open University. His research interests include shape transformations in design exploration, generative product design, and computational design. Prior to beginning his academic research career he worked in industry as a product designer. He received his degree in industrial design engineering from the University of Girona.

Chris Earl has been a member of the Department of Design and Innovation at the Open University since 2000, where his main research areas are generative design descriptions, shape representations in design, and planning complex design processes. While at the University of Newcastle, Department of Mechanical Engineering and Engineering Design Centre between 1991 and 2000, Dr. Earl conducted interdisciplinary research on the design of complex engineered to order products and on planning their manufacture and assembly. He has degrees in mathematics and a PhD in design.

Steve Garner is a Senior Lecturer in the Department of Design and Innovation at The Open University. He is the Academic Team Chairman for The Open University Design and Designing course. His research interests include the function and value of sketch representations in design, computer supported collaborative design, and the involvement of older users in product design and development. He has published widely on design principles and practices and on design education.

Iestyn Jowers is currently both a research student at The Open University and a Research Associate at the University of Cambridge. As a research student he is working toward a PhD in computational design and is investigating theoretical and practical issues concerning implementing shape grammars on curved shapes. As a Research Associate he is part of a project that is aiming to identify approaches to information and knowledge management that may be applied to the through life support of long-lived, complex engineered products.